Future Missions to Study Signposts of Planets

interferometry, history

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Signposts of Planets Conference, GSFC
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This talk …

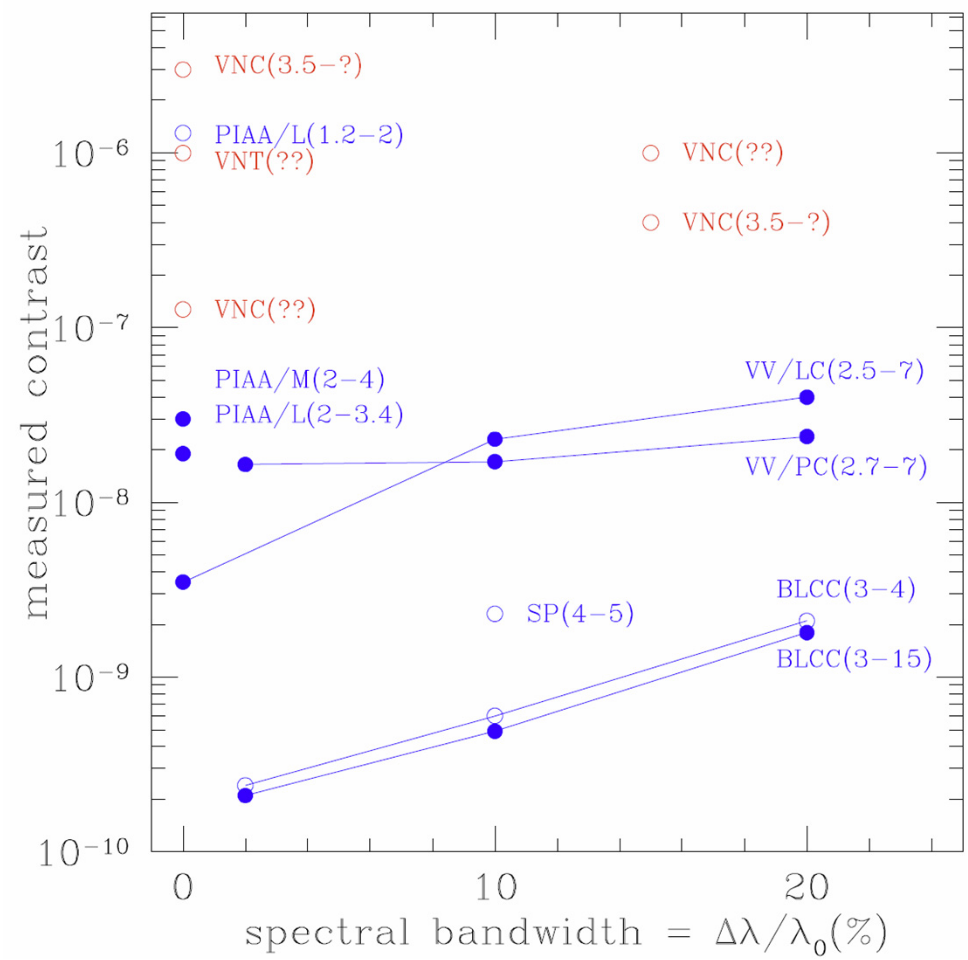
- Will not address:
  - JWST (see Mark Clampin's talk)
  - Herschel (see Brenda Matthews' talk)
  - ALMA (see …)
  - HST (see Glenn Schneider's & Karl Stapelfeldt's talk)
  - Sub-mm (see David Wilner's & Meredith Hughes' talks)

- Will focus on debris disks (easier), not exoplanets (harder).
- Will compare ground and space.
- Will discuss 2 proposed missions, EXCEDE & Zodiac II.

Contrast-bandwidth plot

- Current status of coronagraph experiments is shown.

- BLCC = band-limited complex coron.
- SP = shaped pupil
- VV/PC = vector vortex, photonic crystal
- VV/LC = vector vortex, liquid crystal
- PIAA = phase-induced amplitude apodization
- VNC = visible nuller coron.
- VNT = visible nuller testbed
- EO = external occulter



Ground-based contrast limit

α = local slope of wavefront

n = no. of electrons in Shack-Hartmann sub-pupil image

$\Delta\alpha = \lambda/(r_0\sqrt{n})$ radian = ang. accuracy of image centroid

$h_{rms} = \Delta\alpha \times r_0 = \frac{\lambda}{\sqrt{n}}$ = uncertainty in delay of wavefront patch

$h_{rms} = \frac{N_{DM}\lambda\sqrt{C}}{4\sqrt{\pi}}$ = wavefront error corresp. to contrast C

$n = \frac{16\pi r_0^2}{CD^2}$ = no. of electrons in r_0 with contrast C & tel. D

$n = 10^{a-0.4m}(0.2\lambda)\left(\frac{\pi}{4}r_0^2\right)\left(0.31\frac{r_0}{V}\right)\left(\frac{QE \times \lambda}{2 \times 10^{-12}}\right)$ = no. elec. from star in wavefront patch

$r_0(\lambda) = r_0(\lambda_V)(\lambda/\lambda_V)^{6/5}$ = r_0 as fn. of λ

$m = 2.5\left[a + 10.69 + 3.2\log(\lambda_{\mu m}) + \log(CD_m^2)\right]$ = $13.6 + 2.5\log C + 5\log D_m$ (mag, VRIJHK)

So: D_m=8m & $C=10^{-7}$ requires m=0.6 mag, ground-based,
& with m=5.6 can get $C=10^{-5}$ raw contrast.

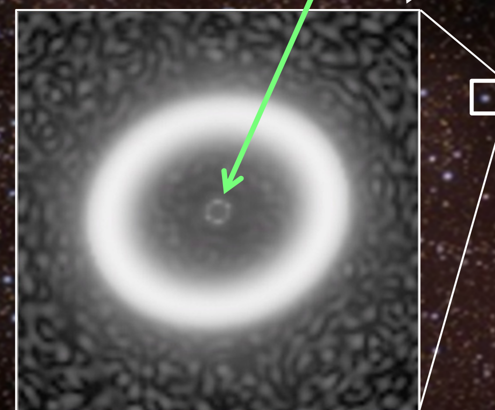
Ref.: Traub & Oppenheimer, in Exoplanets (p. 146).

EXCEDE

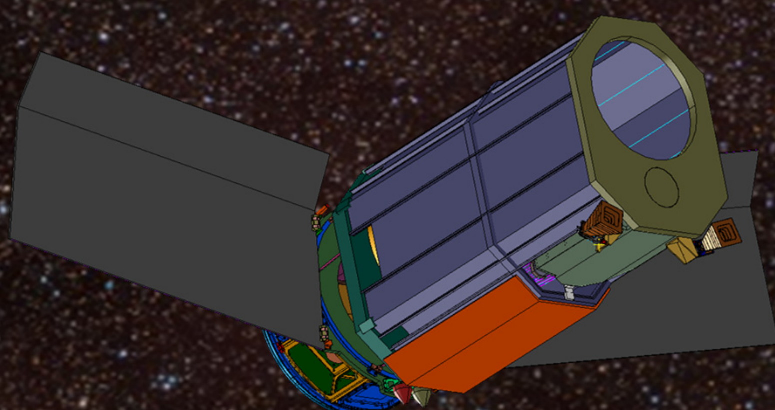
Credit: G. Schneider

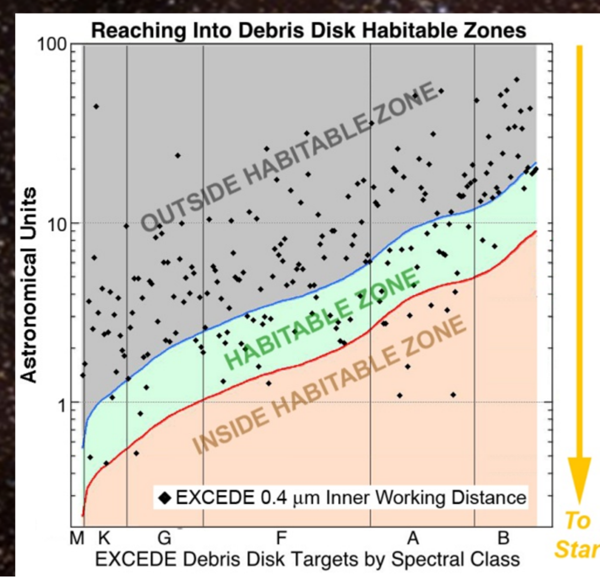
EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

Studying the formation, evolution, and architectures of exoplanetary systems, and characterizing circumstellar environments in habitable zones.



Dr. Glenn Schneider
Steward Observatory
The University of Arizona





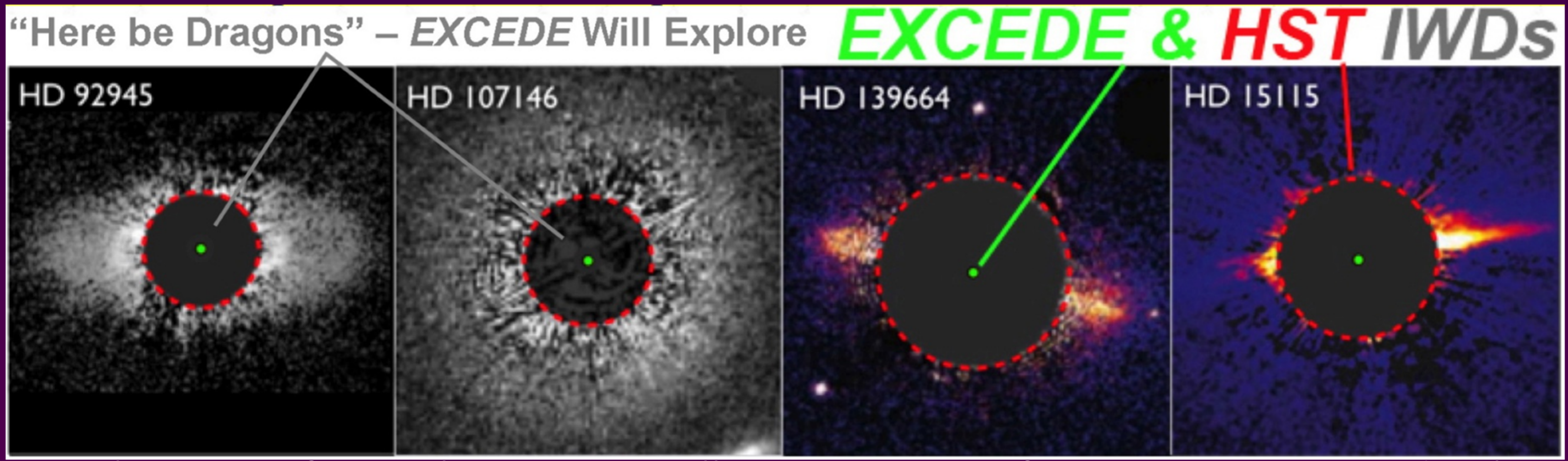
A Response to NASA's 01 Nov 2010
Announcement of Opportunity
NNH11ZDA002O
EXPLORER 2011

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

Using Disks to Discover the Diversity of Planetary Systems

Credit: G. Schneider

- Scattered-light images provide the greatest insights because they trace dust at a wide range of stellocentric distances, but…
- No existing coronagraphs have sufficiently small inner working angles and disk-to-star image contrast sensitivity to probe CS disk systems. in their habitable zones (where the Earth resides in our solar system).
- Dynamical interactions between planets and disks are predicted to play vital roles in generating the architectures of planetary systems, but the inner regions of such systems, today, remain obscured.



HST optical images of CS Disks. *EXCEDE will image ~ 1000x fainter in contrast and at least 3x closer to their stars and at spatial resolutions comparable to the best JWST will deliver.*

Credit: G. Schneider

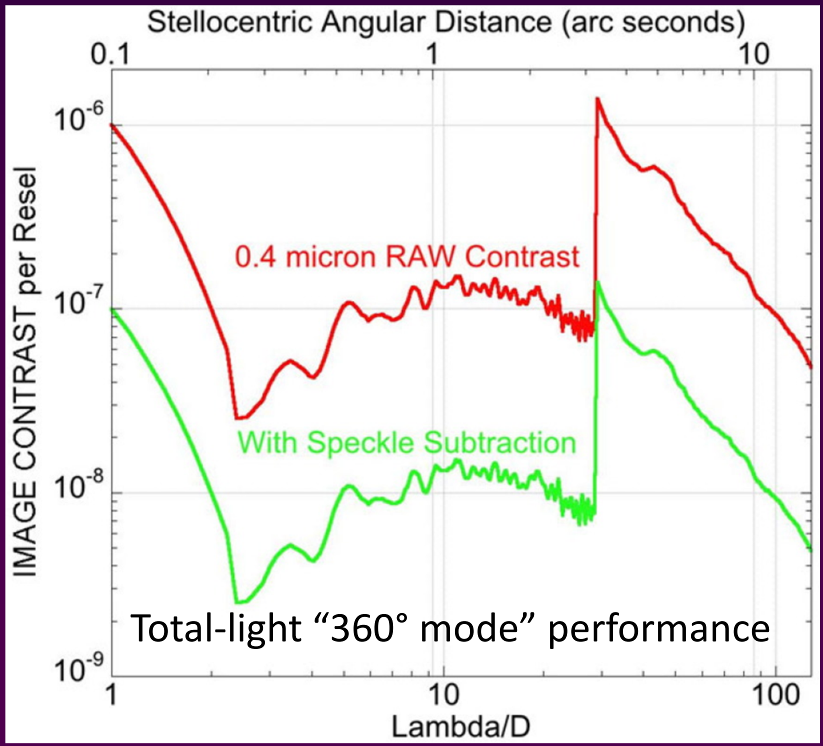
The Need for *EXCEDE*

EXCEDE fulfills the capability currently lacking in NASA's mission portfolio to achieve the today's key exoplanetary science goals.

A large aperture telescope is not require to meet EXCEDE's scientific objectives. Imaging CS dust at small IWA is a contrast, not photon, limited problem.

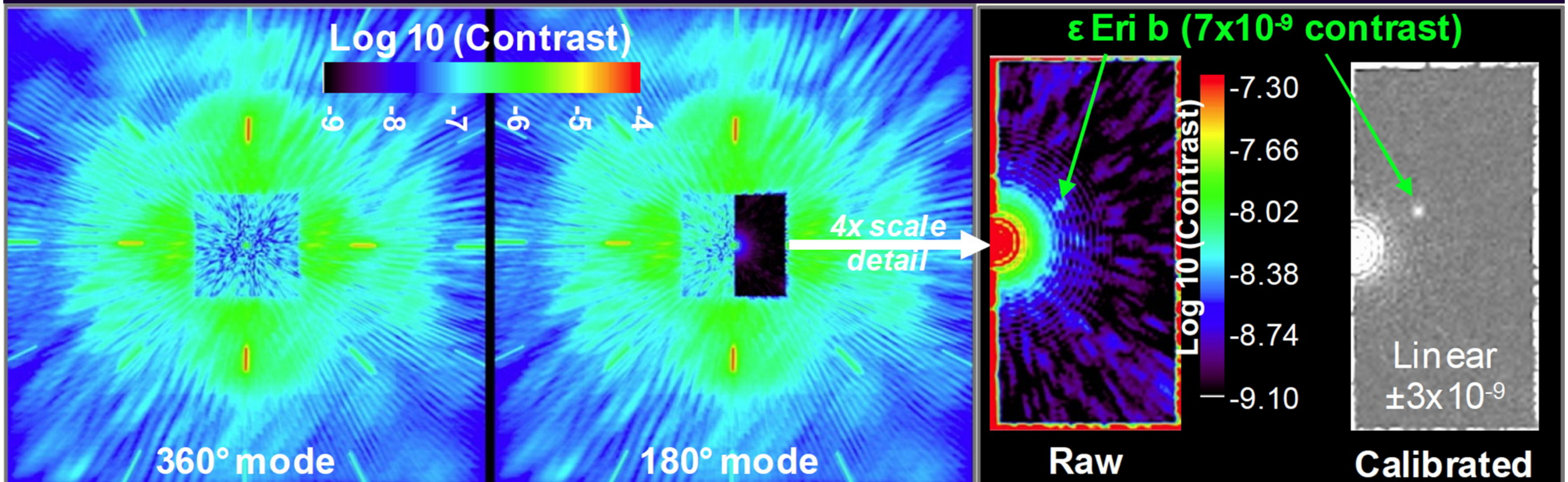
Imaging Sensitivity to ~ 10 zodi disks & mature EGPs

- Diffraction-limited polarimetric & total light imaging in 2-bands: 0.4 & 0.8 μm (spatial resolution 0.14" and 0.28").
- 1.2 λ/D inner working angle (IWA) (IWA at the diffraction limit)
- < 10^{-8} resel^{-1} speckle-subtracted image contrast @ 2 – ~30 λ/D
- ($10^{-7\,-\,-8}$ @ 1.2 – 2.0 λ/D)
- Photon-limited polarized flux contrast augmentation (x10 – 100)



EXCEDE **— EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER**

STARLIGHT SUPPRESSION with PIAA Coronagraph & DM WF Control



- Image contrasts < 10^{-7} and 10^{-8} are achieved within the DM WF control zone (< 28 λ/D; ~ 7” x 7” FOV @ 0.4 μm in 360° (disk survey) and 180° (faint-disk follow-up and planet imaging) modes.
- PSFs shown with 1 mas target centering error and 10 inoperable DM actuators (worse than current GPI yield).
- ε Eri b @ 3.3 AU (9 λ/D) in *single* 3 hr simulated raw and calibrated images (90% speckle subtraction, photon, and 1.4% flat field noise).

Credit: G. Schneider

EXCEDE — EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

EXCEDE DISK IMAGE SIMULATIONS

Credit: G. Schneider

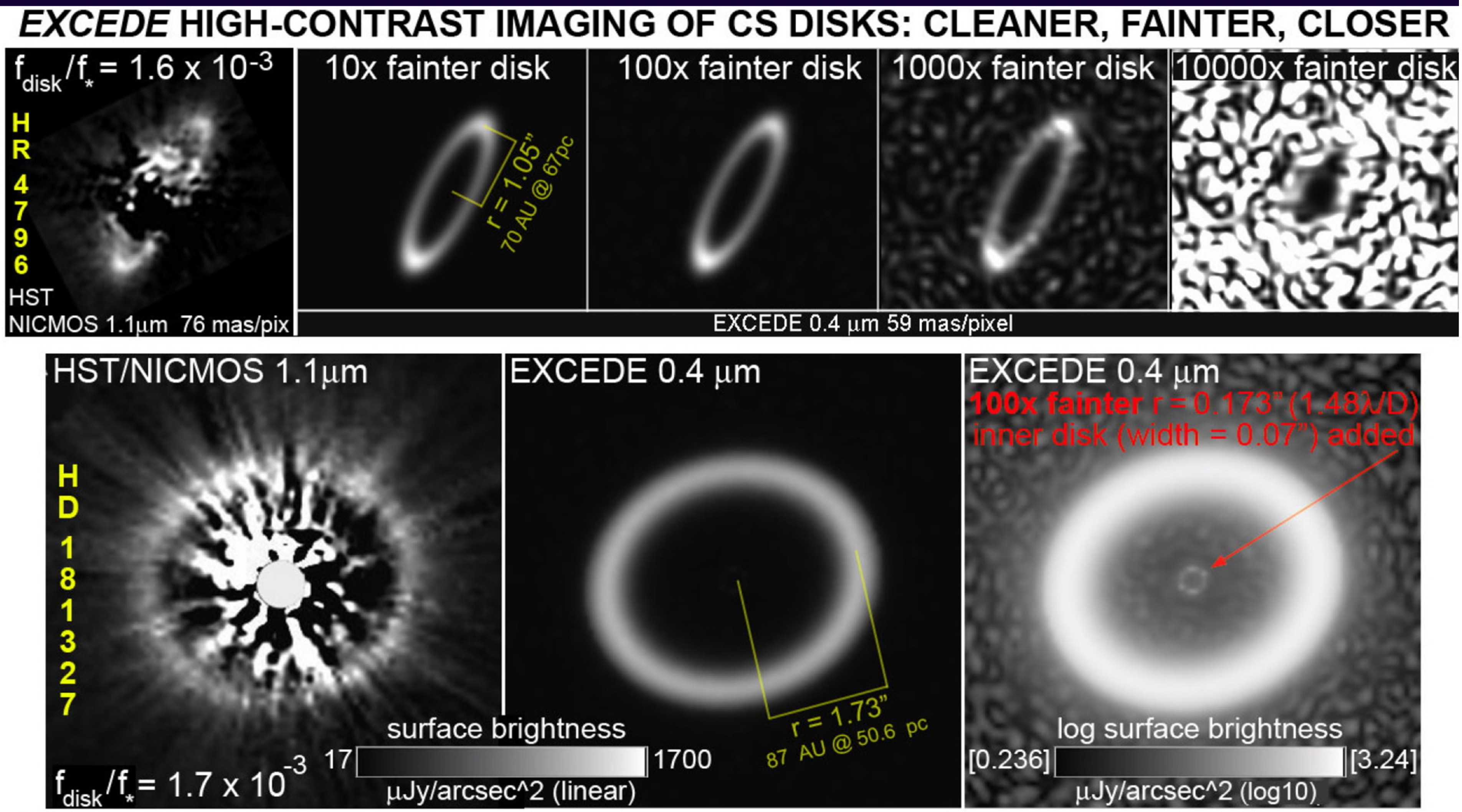
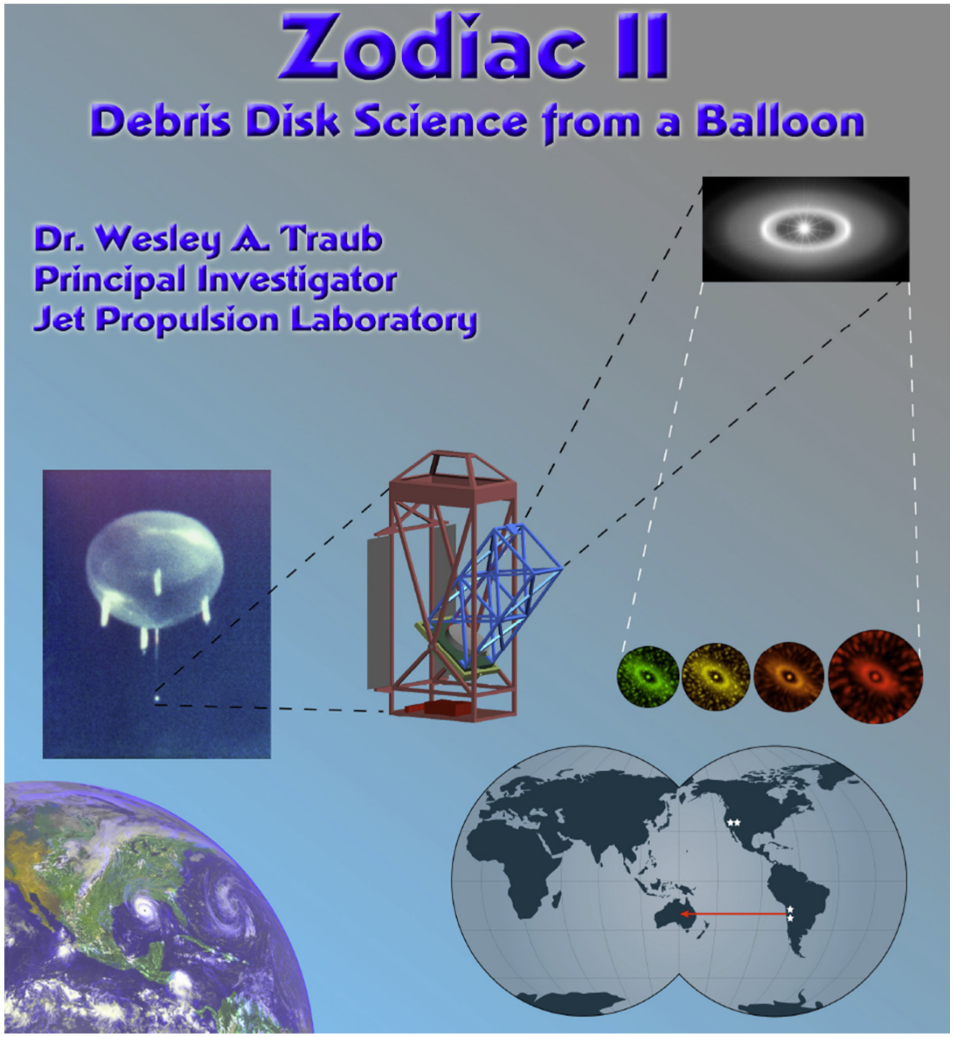


Fig. D.1.10. Pushing *far* beyond the *HST* envelope, *EXCEDE* opens up new observational domains in disk surface brightness and inner working angle. *HST* debris disk images (far left) compared to models of those disks in *EXCEDE* image simulations based on anticipated instrument performance.

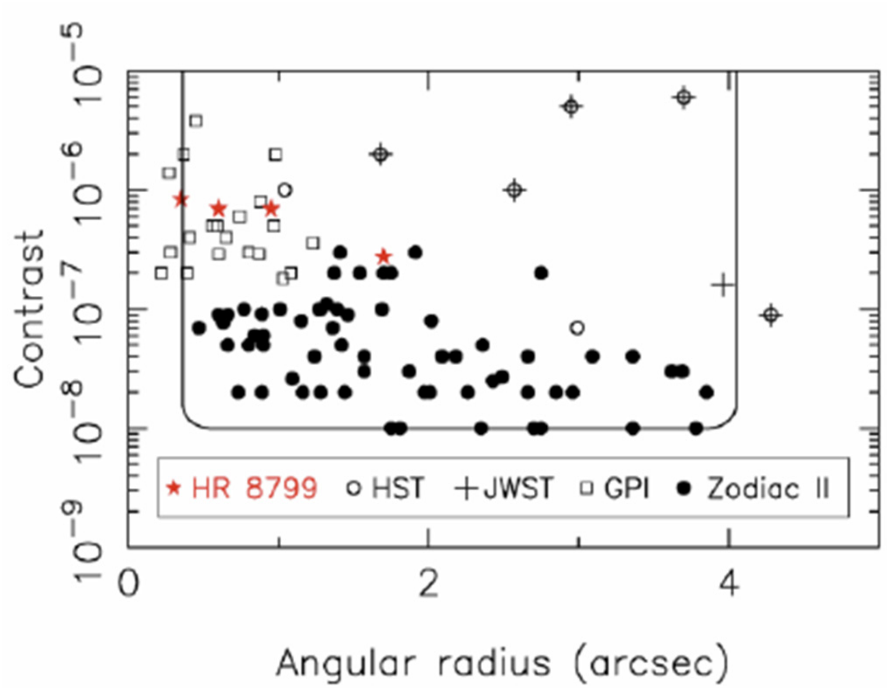


Zodiac II charts

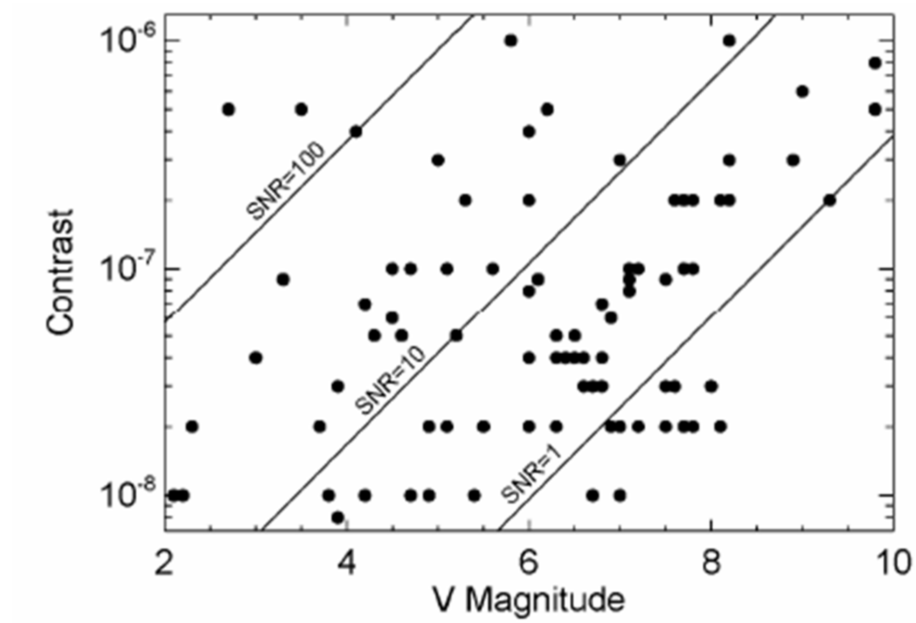
Science Goals	Science Objectives	Scientific Measurement Requirements: Observables	Scientific Measurement Requirements: Physical parameters	Instrument Functional Requirements
Evolution of planetary systems	Measure brightness and shape of debris disks	Disk brightness in radial and azimuthal directions	Surface density profile of scattering dust grains	Processed Image Contrast $\lesssim 3 \times 10^{-8}$
Debris disk origin, shaping, materials, dust production and lifetime	Measure dust size/color	Dust Color	Dust grain size	Images in at least 2 wavebands
		Asymmetry in disk brightness	Debris disk structure	OWA ≥ 3"
	Resolve debris disk structure			Angular Resolution 0.2"/resolution element
Hot, young exoplanets	Measure bright young planets	Visible-light image of the inner disk	Innermost location of detected dust; slope of radial profile	IWA ≤ 0.4"
	Observe 18–25 targets			SNR / hour ≥ 3

Pointing & Wavefront Control

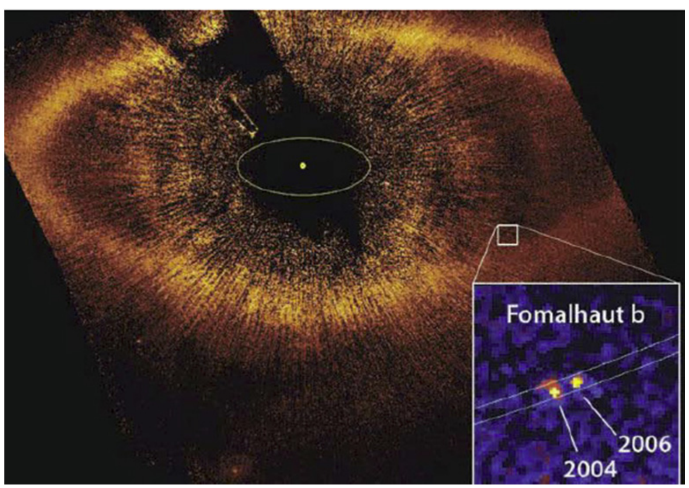
- Image positioning to 0.02 arcsec RMS (requirement is 0.04 arcsec)
  - German/U.S. Sunrise balloon focal plane achieved 0.04 arcsec in 2009
- Wavefront control is 0.3 nm RMS (require 1 nm)
  - JPL High Contrast Imaging Testbed demonstrated 0.05 nm in 2006

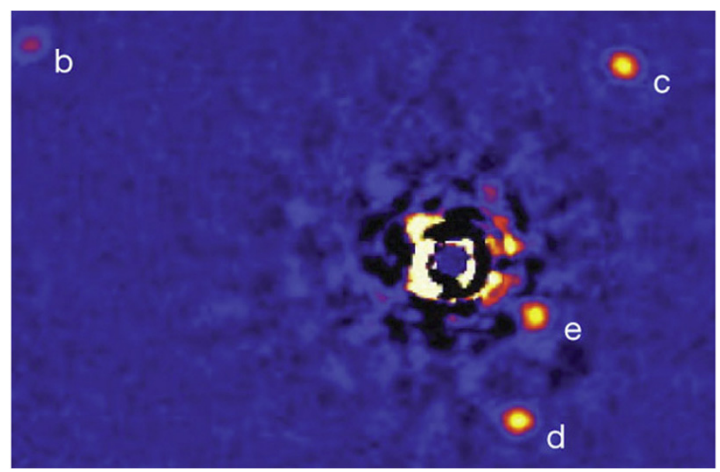


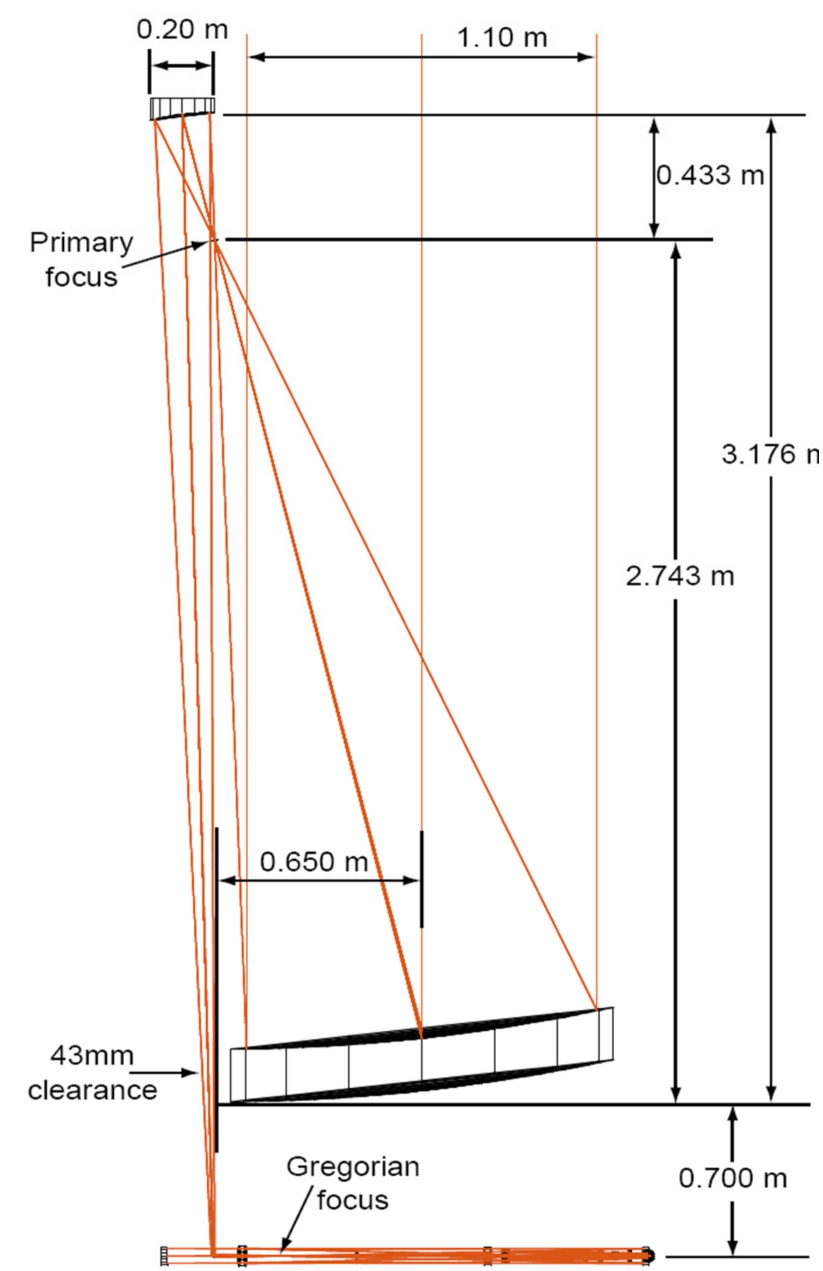
Contrast vs angular separation for 89 targets.



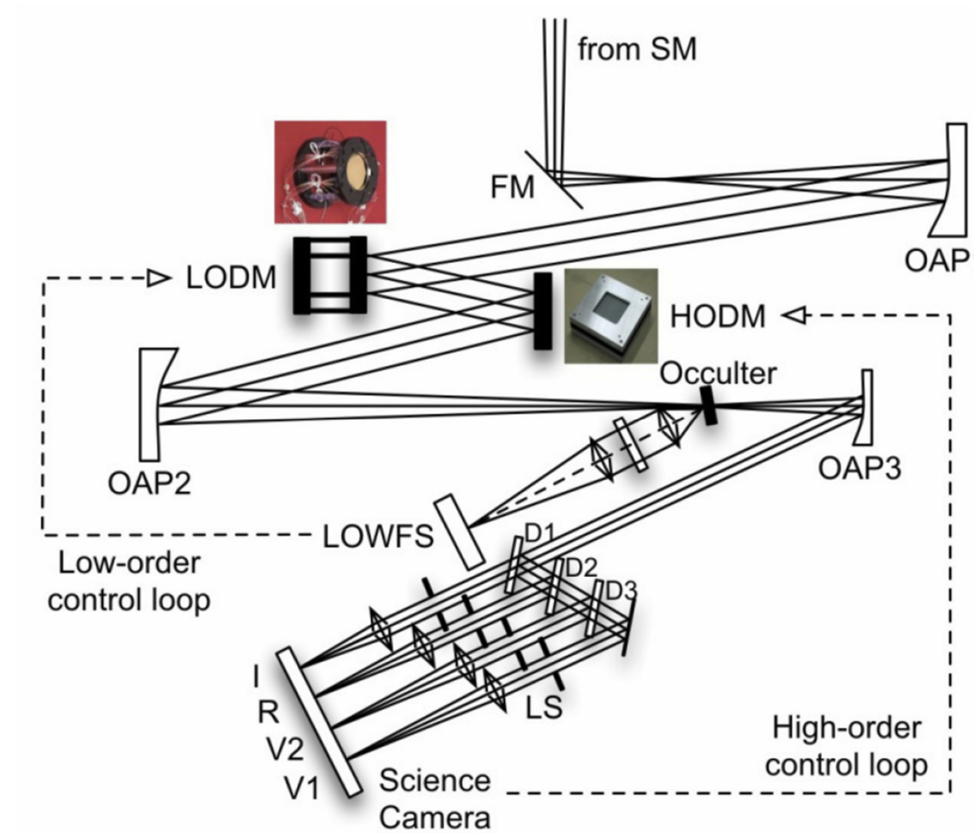
SNR, contrast, & magnitude for 89 targets.



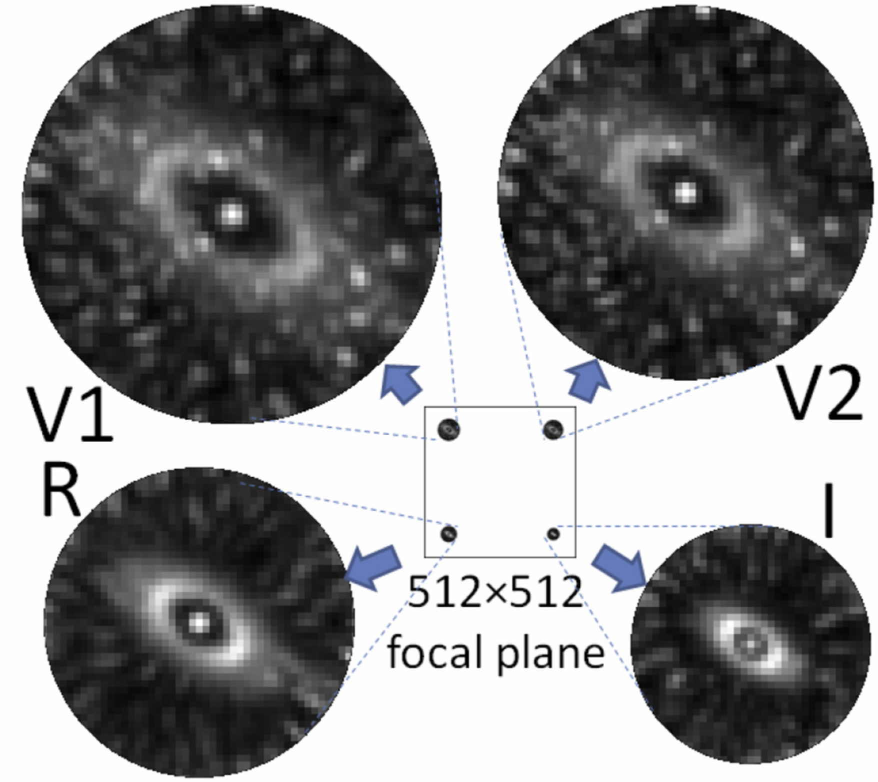




Telescope optical schematic.



Tip-tilt, LODM, HODM, LOWFS, coronagraph, & color filters.


V1
V2
R
I
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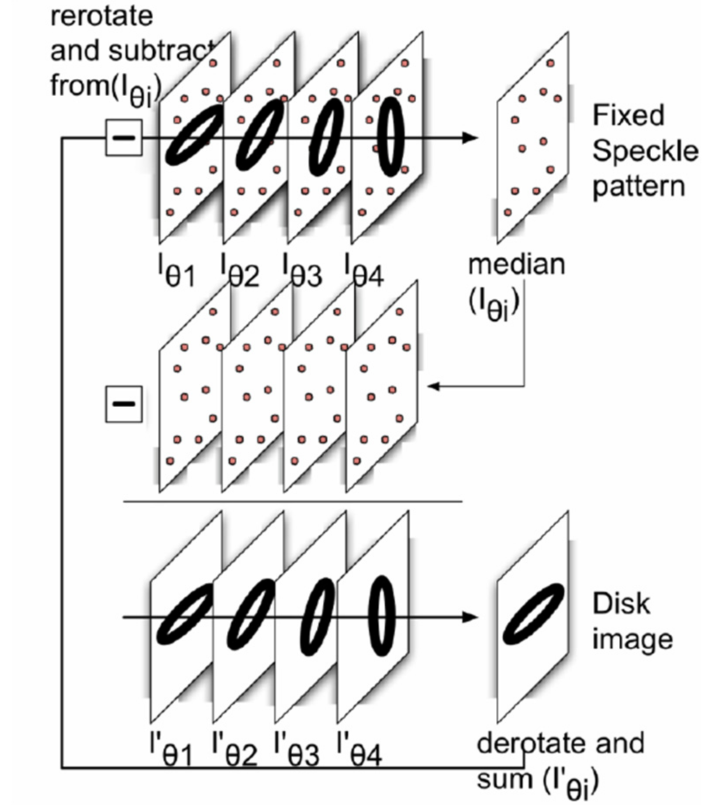
focal plane


rerotate
and subtract
from($I_{\theta i}$)
Fixed
Speckle
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Disk
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$I'_{\theta 1}$ $I'_{\theta 2}$ $I'_{\theta 3}$ $I'_{\theta 4}$
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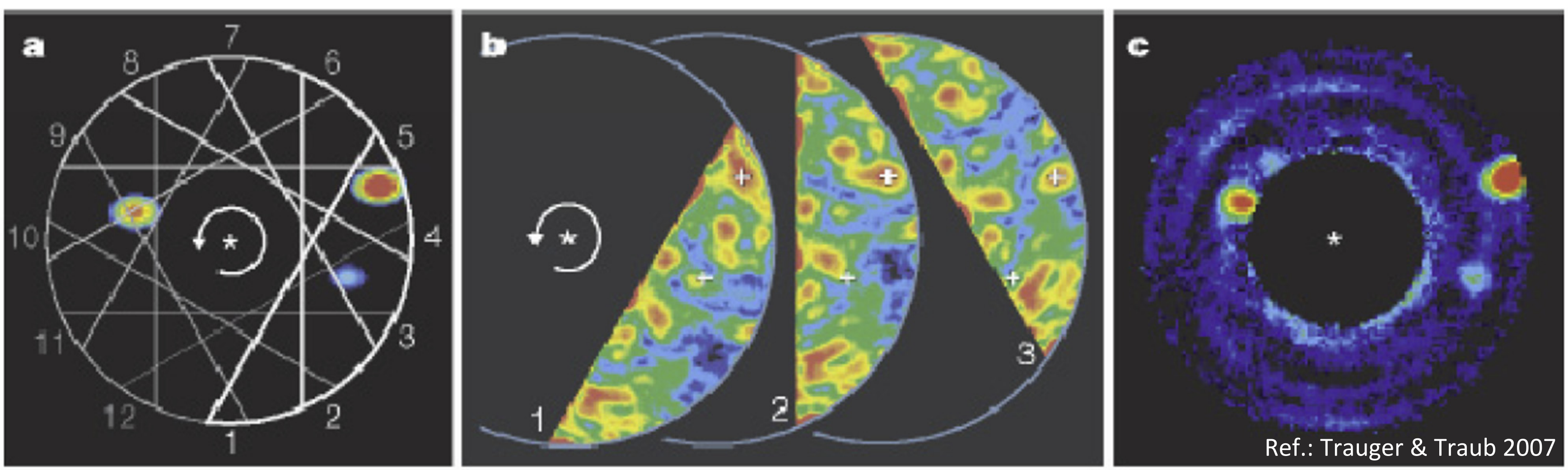
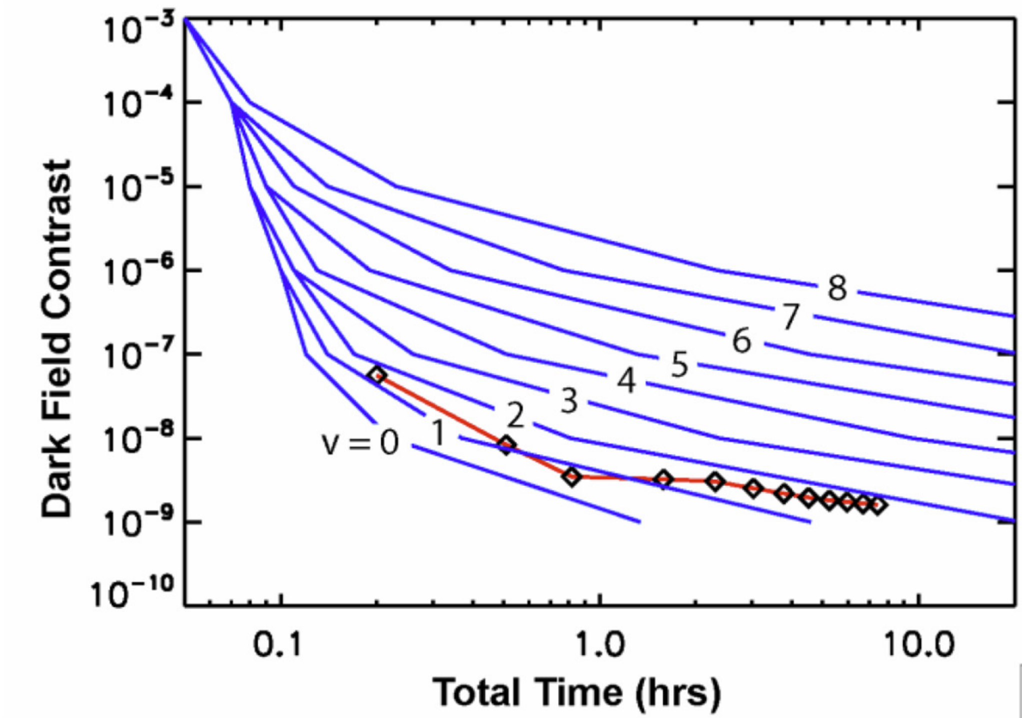
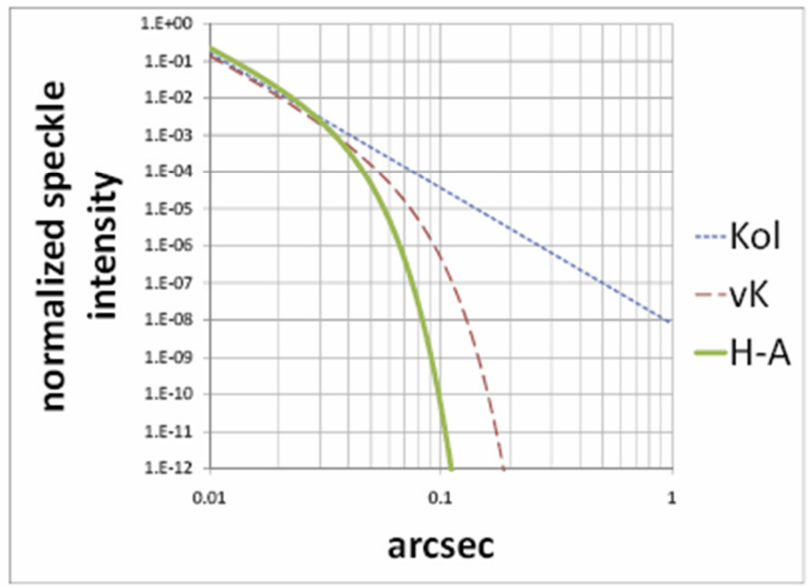
sum ($I'_{\theta i}$)

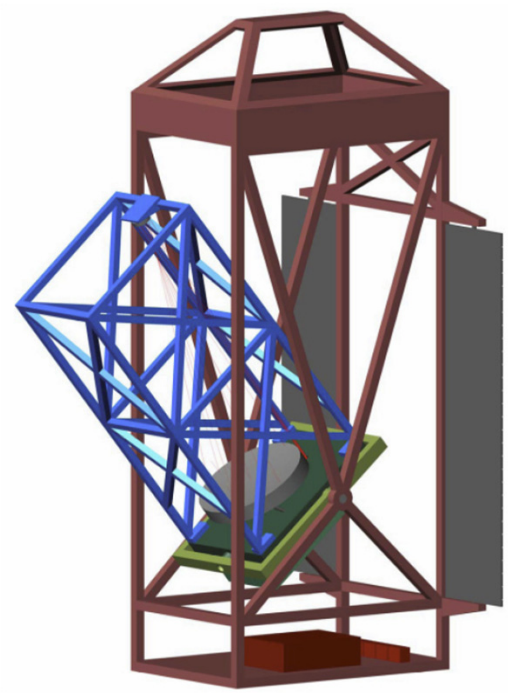

a
b
c
Ref.: Trauger & Traub 2007



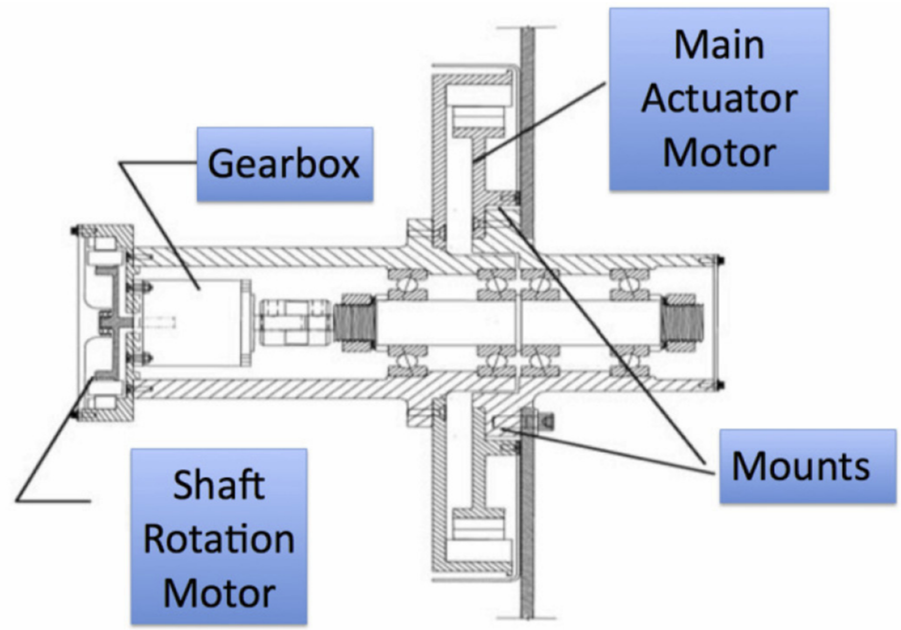
Time to achieve $C=10^{-7}$ contrast is ~20 minutes on a V=3 mag star, calculated & lab-validated.

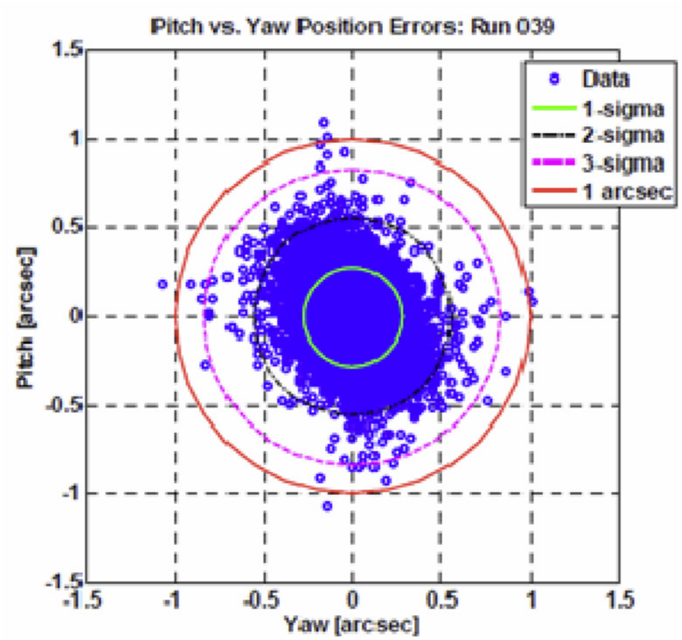


Speckles at balloon altitude expected to have $C<<10^{-7}$ at angles > 0.1 arcsec, from Mir observations.



Low-noise bearings for elevation and cross-elevation axes.





Measured residual tip-tilt is 0.25 arcsec RMS, less than 0.4 acsec reqm't.

Summary

- At least 2 missions have been proposed for disk imaging.
- The technology is largely in hand today.
- A small mission would do excellent disk science, and would test technology for a future large mission for planets.